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FINAL REPORT ON

DESIGN AND CONSTRUCTION OF 4.2°K MASER REFRIGERATOR SYSTEM

for

JET PROPULSION LABORATORY

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

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December 1, 1962

Arthur D. Little, Inc.

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TABLE OF CONTENTS

		Page
I.	INTRODUCTION	1
II.	OBJECTIVE OF WORK	2
III.	SUMMARY OF RESULTS	5
IV.	HISTORY OF PROJECT	6

APPENDICES

A. PHOTOGRAPHS

B. "A NEW REFRIGERATION SYSTEM FOR 4.2K"
by William E. Gifford and Thomas E. Hoffman

I. INTRODUCTION

On April 17, 1961, Arthur D. Little, Inc., (ADL) began a program to design, build, and test a liquid helium temperature refrigeration system for Jet Propulsion Laboratory (JPL) as specified in NASw Contract 950076. This refrigerator, an adaptation of the ADL CRYODYNE Helium Refrigerator, was to be used to cool a maser initially in a laboratory installation and ultimately on the JPL Goldstone antenna. The complete system for use on the Goldstone antenna was to include the necessary antenna piping. The equipment was delivered and successfully operated in the JPL laboratory in January, 1962. The antenna piping system was delivered to the Goldstone antenna site on February 5, 1962.

II. OBJECTIVE OF WORK

The system which was proposed to JPL was essentially similar to systems we had built or were building for other applications. The system was to consist mainly of a refrigerator unit within which JPL's maser would mount, a separately mounted compressor unit, including necessary electrical controls and protective devices, and helium gas piping between these two units, including a piping valve panel. However, this system was to incorporate design changes to allow the JPL maser to be cooled by conduction when inserted into a well in the refrigerator and to provide for a refrigerator external configuration, including mounts, which would be compatible with mounting and operation on the Goldstone antenna. The complete closed-cycle system would require only electrical power and access to cooling air for operation. The refrigerator unit, which could operate in any orientation, would mount directly on the antenna dish, while the compressor unit could be positioned remotely either on the ground or on the stationary portion of the antenna mount.

The system which was chosen for JPL's application is described by the following specifications:

Operating temperature	nominally $4.2^{\circ}K$
Temperature stability	better than $\pm 0.06^{\circ}K$
Refrigeration capacity	greater than 200 mw
Ambient conditions	$0^{\circ}F$ to $+160^{\circ}F$
Orientation requirements	refrigerator operates in any orientation; compressor must remain horizontal
Service life	designed for greater than 10,000 hours
Maintenance period	minimum of 1,000 hours between maintenance shutdowns
Refrigerator size and weight	approximately 10 in. x 15 in. x 36 in.; 115 lbs.
Compressor size and weight	approximately 20 in. x 22 in. x 75 in.; 675 lbs.
Power requirements	refrigerator - 110 w compressor - 3 kw

A paper entitled "A New Refrigeration System for 4.2K" by William E. Gifford and Thomas E. Hoffman which describes more fully this type of refrigeration system is included as Appendix B.

In order to supply JPL with a refrigeration system suitable to cool the specified maser and which was compatible with the proposed laboratory and antenna installations, we proposed the following two-phase program:

Phase I. Basic Refrigeration System - Adaptation to JPL Installation

This phase was to consist of an initial design effort of approximately one and a half months' duration during which time all of the JPL requirements would be reviewed with respect to our existing design. We would then redesign those assemblies or components affected to be compatible with JPL's mounting or operating requirements. When a mutually satisfactory basis to proceed had been reached, we would initiate fabrication and procurement of all of the items, parts, components, and hardware required to build the refrigeration system. This procurement was estimated to take three months. After procurement of these items, assembly and component testing over a two-month period would take place. The individual units were to be combined into a complete system and to undergo full operational testing in our laboratory which would involve another two-month period.

The final testing of the system would include an acceptance test of a minimum of 100 hours of continuous operation at the specified capacity of 200 milliwatts and the specified temperature of $4.3^{\circ}K$.

Subsequent to the final acceptance test, we would ship all of the system components to a location within the United States designated by JPL. We felt that the acceptance testing, preparation and crating for shipment, and shipment would require an additional month; hence, the system would be delivered on site within 9-1/2 months from the date of JPL's authorization to proceed.

Subsequent to shipping of the first unit for laboratory use, we would provide technical assistance and personnel training during installation, initial startup, and operation for a total period of approximately one month.

Phase II. Antenna Installation

Since all of the basic components and equipment proposed under Phase I will be adaptable to the antenna installation except the piping required to interconnect the refrigerator and compressor units, Phase II consisted of an additional design period of approximately two months in which the detail design for the piping for JPL's particular antenna installation could be worked out and a subsequent three-month period for procurement, fabrication, assembly, test, and shipment of the necessary piping, hardware, and flexible units.

In addition, we proposed to provide technical assistance and engineering supervision during the installation of the piping and the remainder of the refrigerator system on the antenna, initial startup, and operation for a total period of approximately one month. Phase II, if carried out concurrently with Phase I effort, would extend the delivery of the Phase II equipment one month beyond the date of the Phase I equipment delivery.

III. SUMMARY OF RESULTS

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A

In January of 1962 the ADL CRYODYNE Helium Refrigerator was delivered to JPL and operated successfully in the laboratory installation. During subsequent laboratory testing, two refrigerator operating problems became apparent. The first was a loss of vacuum integrity due to refrigerator leaks, and the second was a temperature fluctuation in excess of the specified fluctuation when the refrigerator was operated in various positions. This latter problem was due to insufficient structural support of the refrigerator liquid-helium-temperature stage. The refrigerator was returned to ADL, Cambridge, during March, 1962, where these difficulties were corrected. It was returned to JPL in May, 1962. The refrigerator and compressor have operated successfully since that date.

The antenna piping system was delivered to and installed on the JPL Goldstone antenna during February, 1962. Initial operation in conjunction with the refrigerator and compressor was unsuccessful. Subsequent investigation disclosed that the butyl hose used on the flexible sections of the low-pressure gas line was collapsing during operation. This line was the inner line of a concentric piping arrangement and was surrounded by the intermediate pressure gas. The piping was removed from the antenna by JPL and replaced by a JPL-designed piping system. A complete set of hardward was delivered to JPL by ADL for use in fabricating a second piping system to JPL's design.

Photographs of the various refrigeration system components which were delivered to JPL as part of this contract are shown as the figures in Appendix A of this report.

AUTHOR

IV. HISTORY OF PROJECT

The contract for the refrigeration system was signed at JPL on April 17, 1961, and preliminary design work was initiated at ADL during the third week of April, 1961. A layout of a refrigerator unit was started with the vacuum jacket and well arranged to accommodate the proposed JPL maser. The configuration was based on the maser dimensions supplied by Dr. Higa of JPL at the time the ADL proposal was in preparation and on a basic refrigerator unit of the size and type described in the ADL proposal. In this configuration the maser was to be inserted into a closely fitting refrigerated well and was to be cooled by conduction across the approximately .005-inch radial gap between the maser outside diameter and the well inside diameter. The necessary heat leak and temperature calculations for this configuration were also started. Since the time required to design and fabricate the refrigerator was considerably greater than that for the antenna piping, all efforts in the first part of the assignment were devoted to the refrigerator and compressor design.

The preliminary maser-refrigerator layout and thermal calculations were sent to Dr. Higa on May 11 for his review. On May 22, 1961, A. Rogers, P. Serrell, and A. M. Hatch of ADL visited JPL to discuss this refrigerator preliminary design. After a review of the thermal calculations for this preliminary design and calculations for alternate methods of cooling the maser, it was recommended by ADL and agreed to by Dr. Higa that the final maser package design should be provided with heat stations to allow for mechanical and thermal attachment to the corresponding refrigerator heat stations. This method of conductive cooling would provide a lower temperature differential between the maser and the refrigerator than would the original method. However, since easy insertion and removal of the maser would be desirable during the early stages of the maser-refrigerator test program, it was agreed that ADL would design and construct the refrigerator with a refrigerated well for this initial testing. The well would be removable and would ultimately be replaced by the heat-stationed maser.

In discussing the refrigerator vacuum jacket configuration, it was suggested that ADL investigate the possibility of including provisions which would allow JPL to mount an additional ion-type vacuum pump in the bottom of the vacuum jacket adjacent to the maser. This pump would utilize the magnetic field of the maser permanent magnet and thus eliminate the need for an additional magnet.

During this meeting the possible additional requirement of a coax structure which would be attached between the refrigerator ambient temperature and second-stage (45°K) flanges and which would provide a reference noise temperature measure for the maser was discussed. It was subsequently determined by ADL that this device could be included with the maser package and space and thermal limitations were provided.

The second day of this meeting was devoted primarily to a trip to the Goldstone antenna site where possible arrangements for compressor and piping installation and information on operating conditions were obtained. As a final item, JPL expressed the desire to have the refrigerator, compressor, and laboratory piping delivered sooner than the proposed 9-1/2 months if possible. JPL was to be notified of the possibility of an earlier delivery and its possible effect on contract costs.

As a result of the May 22 meeting, a second refrigerator preliminary design with the necessary thermal calculations was initiated. A copy of this layout was sent to Dr. Higa on June 9 for his review. During this period ADL received from JPL sketches and information concerning JPL's requirements for the refrigerator to antenna mount and for the method of mounting the ion-type vacuum pump in the lower end of the vacuum jacket. A revised copy of the preliminary layout with this information included was sent to Dr. Higa on July 6.

Detailed design, drafting, and fabrication of the refrigerator and compressor were initiated during June, 1961. All design work was complete by September 30, 1961, and all fabrication of these components plus laboratory piping and valve panel was complete by October 30, 1961.

Preliminary design of the antenna piping system for use on the Goldstone antenna was initiated during May, 1961, and was completed in August, 1961. At a design review meeting at JPL on September 7, this preliminary design was reviewed and accepted with minor changes. At this time it was pointed out that the refrigerator was to be mounted in a Cassegrain cone on the antenna dish rather than at the focal point of the antenna dish as previously planned. The design of the upper section of the antenna piping was altered to reflect this change. Detailed design of the piping system was initiated during September, and fabrication commenced during October. Fabrication and testing of the piping system was completed during the latter part of January, 1962.

At the above-mentioned September 7 design review meeting, the refrigerator design and the two mating maser designs were briefly reviewed. There were no points of controversy on these designs, and maser outline drawings of the two maser configurations were sent to Dr. Higa on October 5. These drawings were in sufficient detail to enable JPL to construct masers which could be mated with and cooled by the refrigerator. The proposed antenna installation wiring schematic was also reviewed and accepted by JPL.

During August, 1961, a proposal was initiated for an amendment to the existing contract. This amendment was to cover both the additional design work agreed to and the early delivery date requested by Dr. Higa at the May 22, 1961, design review meeting. This proposal was sent to JPL on September 22, 1961. During October, verbal authorization was received from the JPL contract negotiator and work proceeded at ADL in accordance with the amendment.

System testing of the refrigerator, compressor, valve panel, and laboratory piping was initiated at ADL on November 8 and continued through the early part of December, 1961. The results of this test were satisfactory, and the unit was prepared for shipment to JPL. Total testing of this unit at ADL consisted of 279.7 hours of operation, of which approximately 208 hours were at liquid helium temperature. The measured refrigeration capacity available at the liquid-helium-temperature station was well in excess of that required by JPL.

During this test period, training in the installation and operation of this equipment was conducted at ADL for JPL operating personnel.

On December 20, 1961, the JPL CRYODYNE refrigerator system, designed and constructed under Phase I of NASw Contract No. 950076, was shipped from ADL. The only item of Phase I equipment not delivered at this time, the charcoal trap, was being fabricated at Santa Monica for delivery to JPL on or before January 5, 1962.

ADL engineering and technical assistance was provided during January, 1962, to review installation of the refrigerator in the JPL laboratory, for additional training of JPL personnel, for assistance during initial startup, and for the performance of minor crosshead maintenance.

On February 5, 1962, the antenna piping designed and constructed under Phase II of NASw Contract No. 950076 was delivered to the JPL Goldstone antenna site. ADL engineering assistance was also provided to supervise the installation of this piping system on the antenna.

Operation of the refrigerator in the laboratory and subsequently in conjunction with the antenna piping system disclosed a number of operating problems with the delivered equipment. The major refrigerator problems encountered were leaks in the refrigerator internal assembly which destroyed the vacuum integrity and excessive temperature fluctuations at the liquid-helium-temperature flange when the refrigerator was operated in different positions.

After substantial investigation of these problems at JPL during February, 1962, it was the recommendation of ADL engineering personnel that the refrigerator unit be returned to ADL for correction of these difficulties. This was accomplished during March, 1962, and the unit was returned to JPL on May 5, 1962. Operation at JPL upon return of this equipment indicated that both of these difficulties had been corrected to the satisfaction of JPL personnel.

Operation of the refrigerator with the antenna piping at the Goldstone antenna during February, 1962, disclosed an excessive pressure drop in the antenna piping low-pressure line. Subsequent investigation, primarily by JPL personnel, disclosed a collapsing, during operation, of the butyl hose which was used for the flexible sections of the piping system. This low-pressure line was the inner line of a concentric piping arrangement and was surrounded by helium gas at the intermediate pressure level. The differential pressure across the butyl hose was sufficient to collapse the inner sheath.

A decision was made by JPL to remove the complete antenna piping system without allowing ADL to correct this difficulty. JPL then proceeded to construct their own piping system for use on this antenna, and the ADL system was discarded. In an effort to discharge our responsibility to JPL, ADL offered to supply all the hardware required to construct a second antenna piping system to the JPL design. This offer was verbally accepted by Dr. Higa and this material has been delivered.

Operation of the refrigerator with the JPL-designed antenna piping gave very satisfactory results.

As requested in the initial contract, ADL sent to JPL one reproducible copy and three prints of all drawings, with the exception of the antenna piping drawings, which were required to construct this equipment. The antenna piping drawings were not delivered because of the problems which JPL encountered with this equipment and because this equipment was subsequently discarded. Copies of the refrigerator test data were also delivered to JPL.

A brief operating manual was also delivered to JPL, as required by the contract. A more nearly complete operating manual has been written for a similar refrigeration system and this manual is presently being modified for use with the JPL system.

Subsequent to the final delivery and successful operation of this system, ADL has, when required, provided engineering and technical assistance to solve minor field service problems and to assist in the modification of the refrigerator for use with a new Travelling Wave Maser.

APPENDIX A

PHOTOGRAPHS

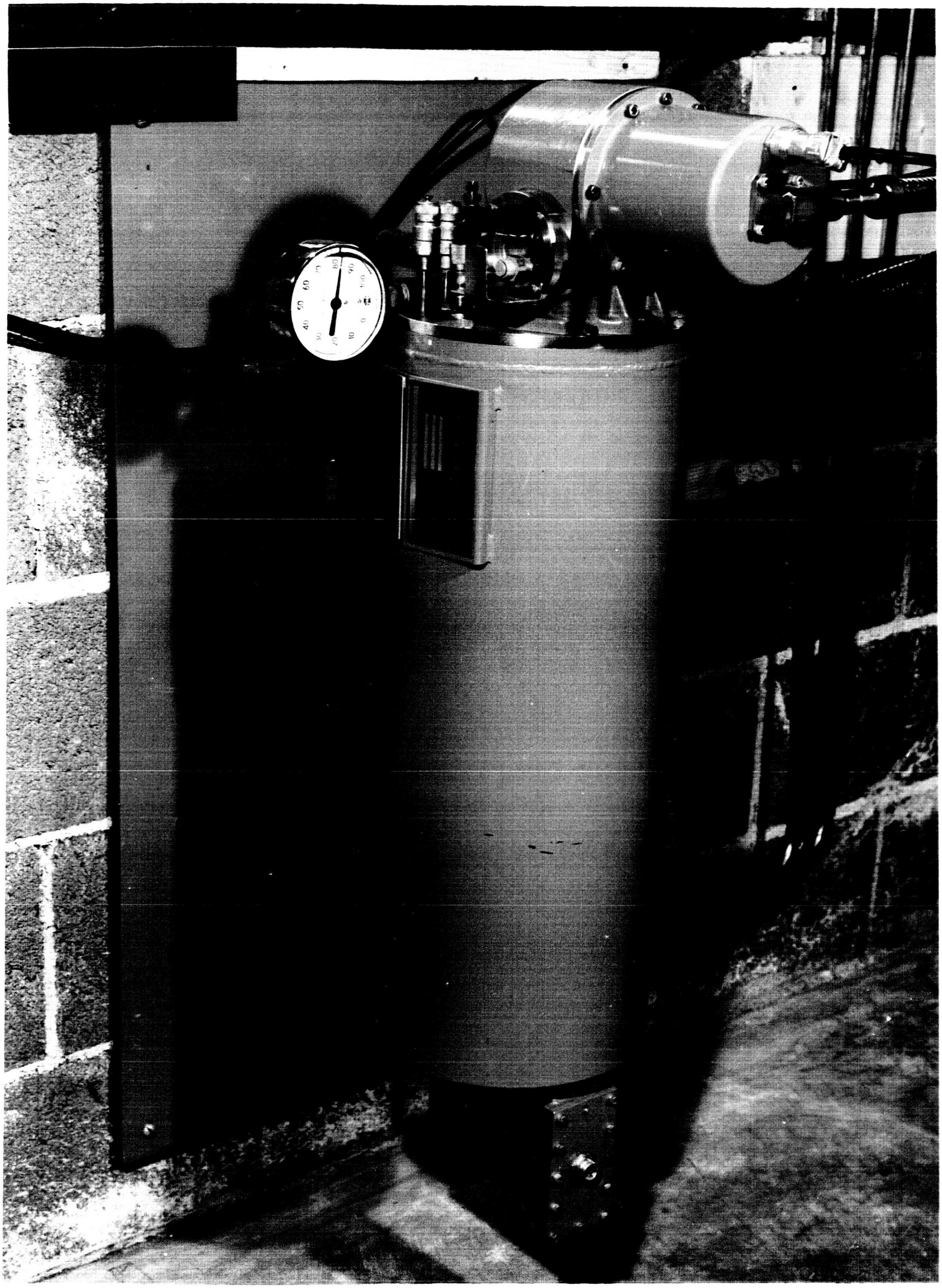

Figure I - CRYODYNE Helium Refrigerator Unit
Left-side View

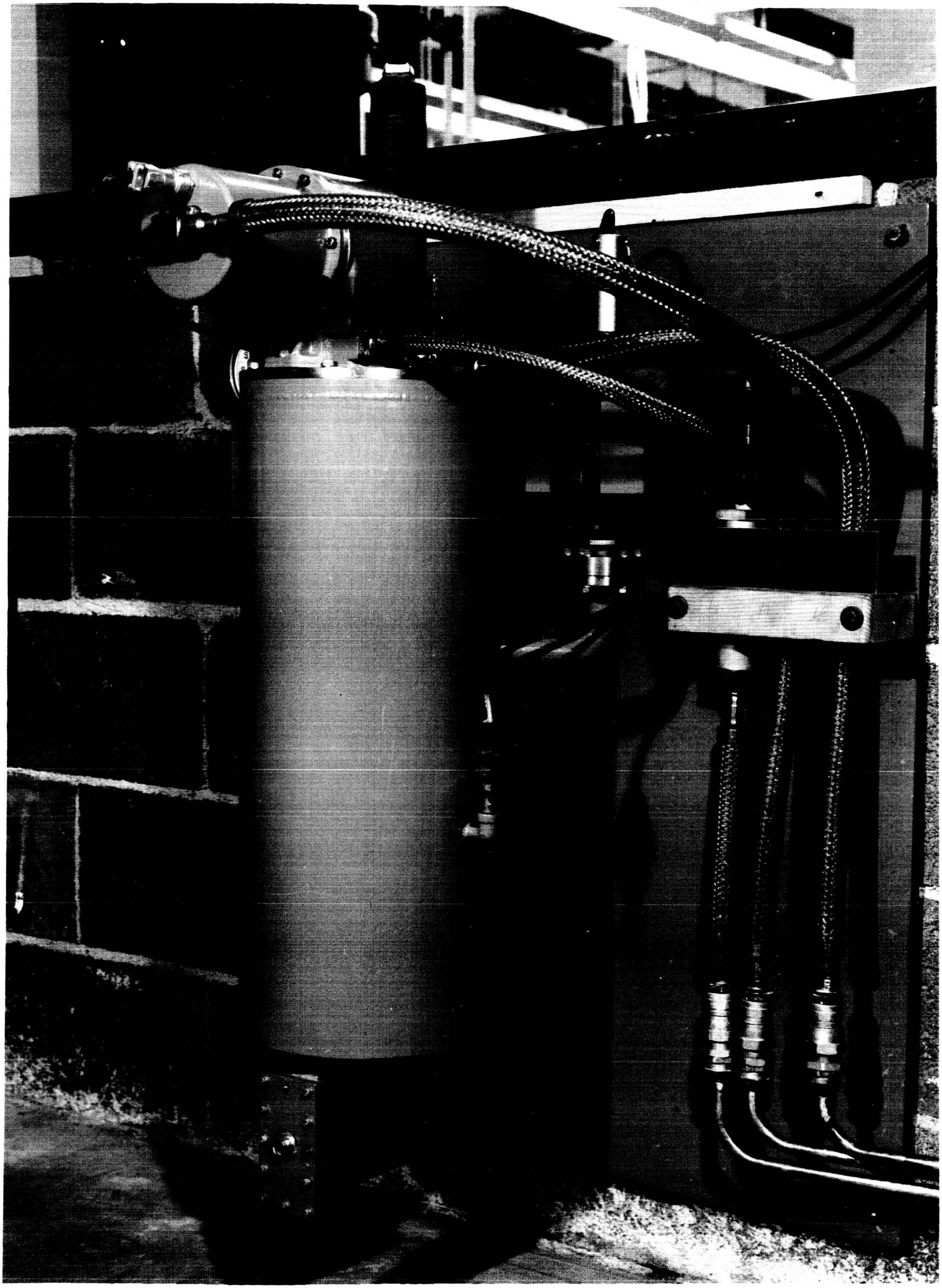

Figure II - CRYODYNE Helium Refrigerator Unit
Right-side View

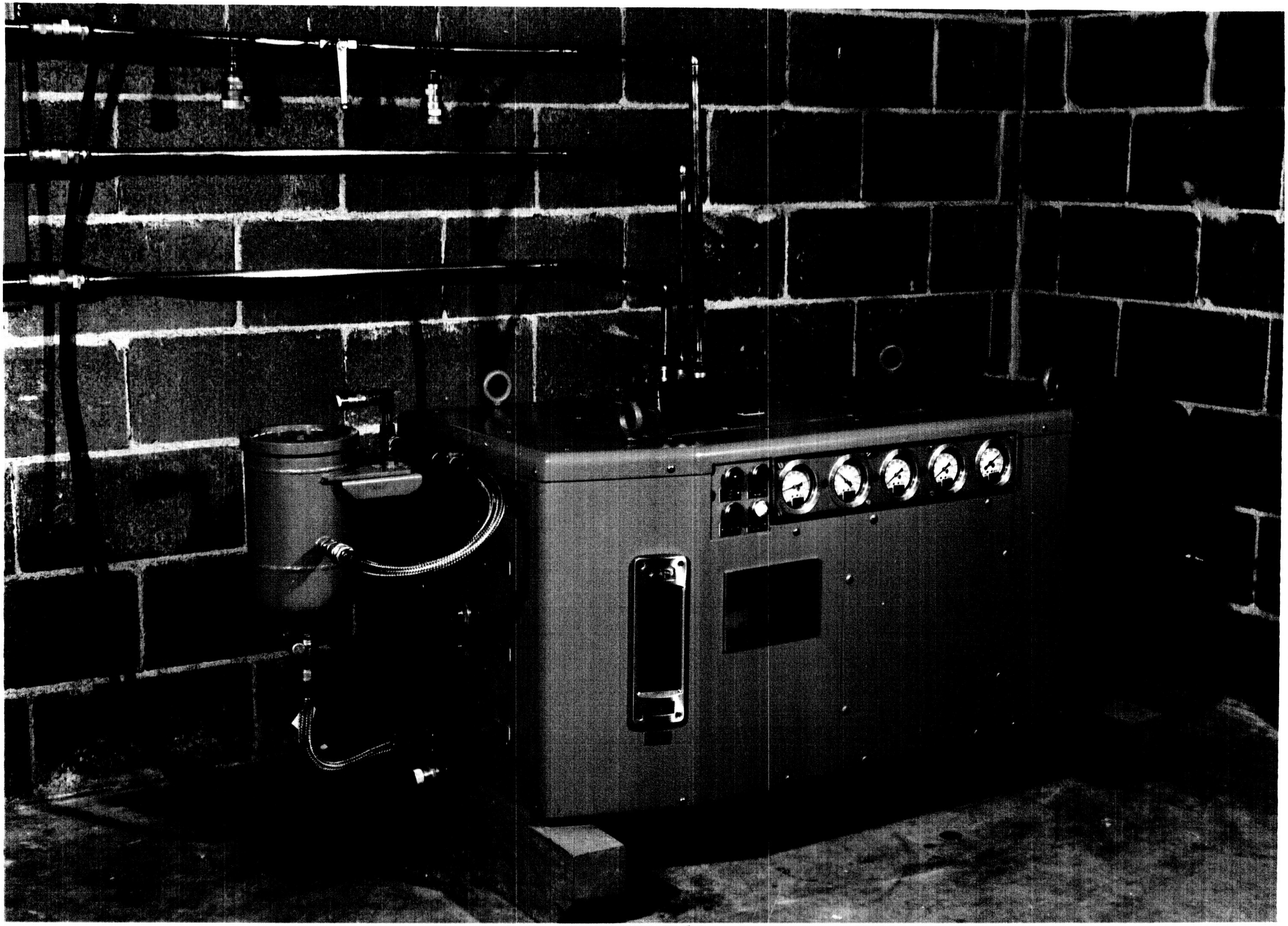

Figure III - CRYODYNE Helium Compressor Unit

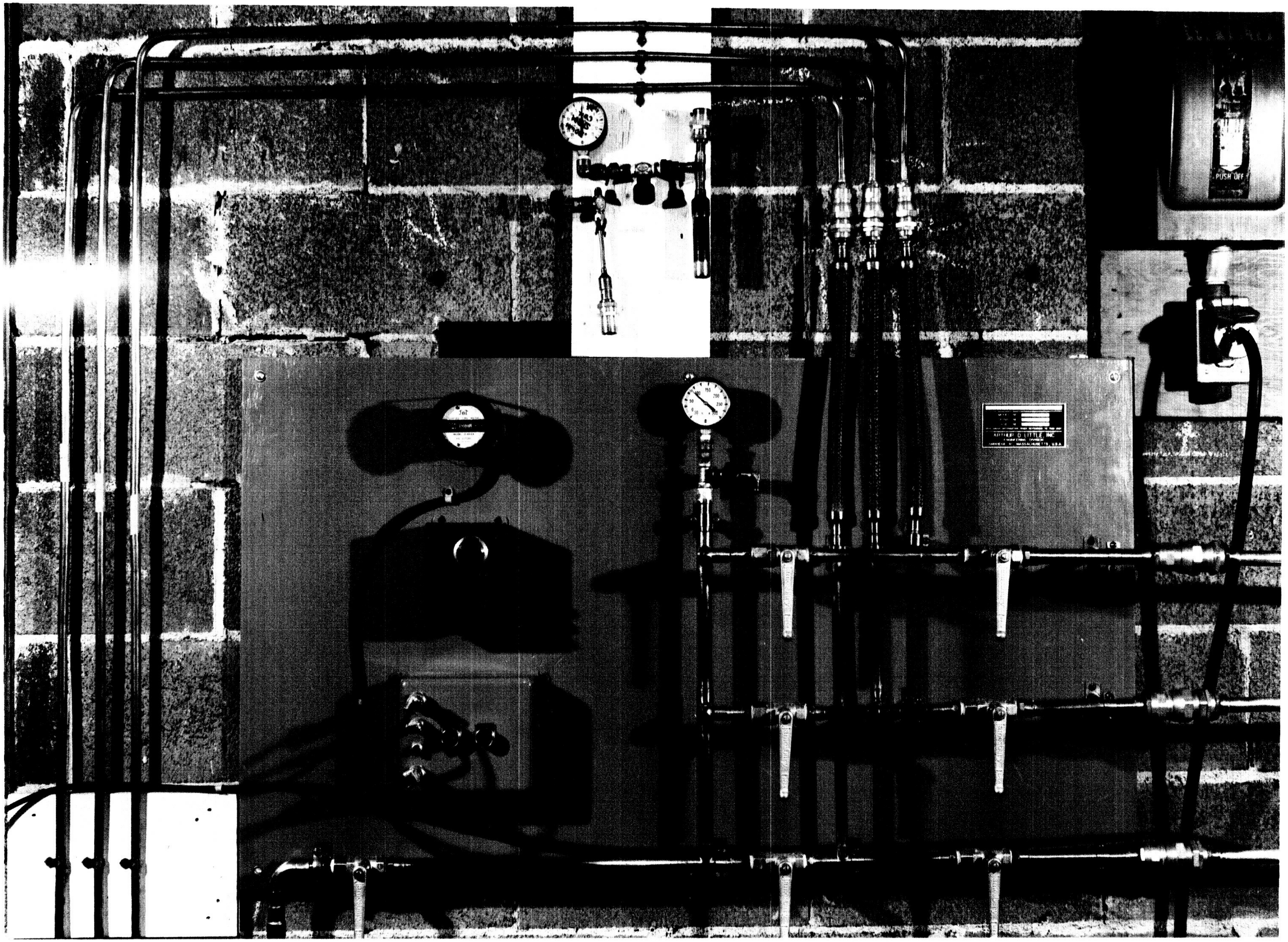

Figure IV - CRYODYNE Helium Refrigeration System
Piping and Control Panel

APPENDIX B

"A NEW REFRIGERATION SYSTEM FOR 4.2K"

by

William E. Gifford and Thomas E. Hoffman

A NEW REFRIGERATION SYSTEM FOR 4.2K

William E. Gifford and Thomas E. Hoffman
Arthur D. Little, Inc.
Cambridge, Massachusetts

Introduction

A year ago, a new refrigeration cycle was described.[1,2] Its basic simplicity showed promise of excellent reliability and ease of construction. It was able to reach 35K and to generate refrigeration efficiently at 60K and above in its most elementary form. The purpose of this paper is to show how the basic method with modifications can be used as the base for a small, simple helium-temperature refrigerator and to describe such an operating refrigerator.

With modifications, the system achieves the effect of several expansion engines operating at different low temperatures. As a result, refrigeration can be generated efficiently at a temperature as low as 14K as well as at several other temperatures, and there is no loss of any of the advantages described for the most elementary refrigerator. These advantages are that:

(1) The valves are still at room temperature, where elastic seals may be used.

(2) There are only two valves, no matter how many equivalent engines might be achieved.

(3) The displacer seals are also at room temperature, where very tight elastic seals may be used.

(4) All the cold regions consist of closed conduits and loosely fitting displacer-cylinder systems.

(5) The system retains the self-cleaning attributes of the elementary system.

Review of Thermodynamics

To understand clearly how this new refrigeration process functions, it is advisable to review the manner in which an ordinary expansion engine generates refrigeration. Its action is more subtle than would at first be supposed.

When a piston-and-cylinder type expansion engine does work adiabatically, as shown in Figure 1a, the gas it is using cools. Thus, it may be used as a refrigerator.

The work performed by the engine is composed of a sum of work performed by the compressor or gas reservoir on the piston $P_1 V_1$, the work performed by the gas expanding $\int_{V_2}^{V_1} PdV$, and negative work performed by the engine back on the compressor or gas reservoir $P_2 V_2$. The total net work is

$$W_k = P_1 V_1 + \int_{V_2}^{V_1} PdV - P_2 V_2 \tag{1}$$

$$W_k = P_1 V_1 + NC_V (T_1 - T_2) - P_2 V_2$$

$$W_k = P_1V_1 + \Delta E - P_2V_2 \tag{2}$$

$$W_k = \Delta H$$

As it performs the work $\int_{V_2}^{V_1} PdV$, the gas cools from T_1 to T_2. However, the refrigeration available from this cold gas is equal to $NC_p(T_1 - T_2)$. It is made available by warming of the gas back to T_1 at constant pressure. Thus, the refrigeration available is more than the work the gas does on the piston in expanding $\int_{V_2}^{V_1} PdV$. It is equal to the total work done on the piston by both the gas and the compressor: $NC_p(T_1 - T_2) = \Delta H$.

Consider now the operation of a gas engine with the cycle shown in Figure 1b. In this case, the intake valve is kept open for the full stroke of the piston, and the gas is allowed to expand when the exhaust valve is opened--without the motion of the piston. No work is done by the engine while the gas is cooling. Therefore, V_1 and V_2 are equal and may be expressed as V. The engine's work is equal to the sum of the work the compressor or gas reservoir does on the engine P_1V and the negative work performed by the engine on the compressor or gas reservoir P_2V; hence, $W_k = (P_1 - P_2)V$. All the work done by the gas during expansion is done on the compressor or the gas reservoir and does not show up in the work performed by the engine.

The net available refrigeration, however, may be shown to be equal to the work the engine does. We can demonstrate this by combining a great number of cycles of the first type (Figure 1a) with small compression ratios, as shown in Figure 1b. Here, we know that the net available refrigeration is equal to the area under the cycles of the first type, and most of the area is enclosed. If an infinite number of these cycles is taken, all the area will be enclosed.

In the same way, it can be proven that for any pressure-volume diagram the area is equal to the net change in enthalpy for adiabatic conditions.

The refrigeration ΔQ_r is not equal to the work the gas does on the engine--or even the work the gas does. It is equal simply to the ideal work of the engine:

$$\Delta Q_r = PdV .$$

A clear and complete statement of the principle would be that for any system which has a variable volume and variable gas pressure a series of operations will describe a closed area on a pressure-volume (P-V) diagram, regardless of the shape; this area will be precisely equal to the net change in enthalpy of the gas involved per cycle (assuming adiabatic conditions). If the area is described in a clockwise direction, the change will be a decrease, making refrigeration available. If the area is described in a counterclockwise direction, the change will be an increase in enthalpy, and heating will result.

Description of the System

The new system, shown schematically in Figure 2, consists of three (two or more could be used) cylinders filled almost entirely with three displacers. The three displacers are held together by a plate; thus, they can be moved in unison by the actuation of a rod. (See Figure 2.)

In this way, four volumes are created that can be varied in size by the motion of the displacer assembly. Volumes 2, 3, and 4 can be made zero if the displacer is moved to its downward-most position, at which time volume 1 is a maximum.

The volumes are interconnected through three regenerators. A set of valves connected to volume 1 allows one to let high-pressure gas into the system or exhaust the system to a lower pressure.

The cycle consists of the following series of operations:

(1) Pressure Build-Up. With displacers at the bottom position, the inlet valve is opened; pressure then builds up in the regenerators and volume 1.

(2) Intake. The displacers are lifted; at this point, high-pressure gas is drawn into volumes 2, 3, and 4 and out of volume 1.

(3) Pressure Let-Down. With displacers at the top position, pressure is dropped by the closing of the inlet valve and the opening of the exhuast valve.

(4) Exhaust. Low-pressure gas is exhausted by the movement of the displacers to the bottom position.

The cycle can then be repeated.

With this series of operations, volumes 2, 3, and 4 describe the clockwise P-V areas, and, as has been shown, they generate useful refrigeration. Volume 1, on the other hand, generates heat as it describes a counterclockwise P-V area equal to the sum of volumes 2, 3, and 4.

The regenerators make the average exhausting-gas temperature from the top of a regenerator only slightly colder than the average entering-gas temperature. (In fact, ΔT's of 1C may be achieved between 80K and room temperature.) The regenerators accomplish this in lengths of 3-4 in. Thus, very little of the refrigeration generated in volumes 2, 3, and 4 is lost to the stage above, and these three volumes can be operated at different temperatures. For the helium refrigerator to be described later, volume 2 operates at 80K, volume 3 at 35K and volume 4 at 14K.

The heat generated in volume 1 at room temperature is ultimately delivered back through the exhaust valve. It is mixed with other gas and delivered into the top of the regenerator at a temperature higher than that of the gas from the compressor. On the exhaust stroke, however, it also exhausts at a temperature very close to the entering temperature, which is higher than the temperature of the gas from the compressor. In this way, heat from volume 1 is carried back to the compressor section.

Figure 3 gives the temperature history of a three-stage system of this type; it shows how the gas passes through the different phases of its operations during one cycle. First, supply gas delivered to volume 1 generates heat. Then gas from volume 1 is mixed with additional gas from the supply before it starts being cooled in regenerator No. 1. By means of the three regenerators, parts of the gas are cooled to three successively lower temperatures and delivered into volumes 2, 3, and 4. The gas then cools by expansion--different amounts in the different volumes--since the cooling of the expanding gas is proportional to absolute temperature.

The gas is warmed back to the temperature at which it was delivered to volumes 2, 3, and 4 by removal of heat from the refrigeration load. This is the useful refrigeration effect; it makes refrigeration available at three different temperatures.

The gas is then warmed back to very nearly the temperature which it previously entered the first regenerator; this means that it is above the temperature of the supply gas. In this way, heat generated in volume 1 is delivered back to the compressor section.

A major advantage of this low-temperature heat-pump cycle is that it is possible to add additional expansion spaces at different temperatures with very little increase in complexity.

The question may be asked: Why is it desirable to have refrigeration supplied at several different temperature levels? There are two very good reasons.

First, it is possible to handle a refrigeration load with a decreased power requirement. Gas-expansion refrigeration devices are, for a constant speed, constant producers of refrigeration independent of the temperature of operation. However, the gas required to operate them is inversely proportional to temperature. Therefore, it takes roughly four times the gas--and thus four times the power--to remove the same quantity of heat at 20K as it does at 80K.

Most low-temperature refrigeration problems require heat removal at several different temperature levels. If the problem is to liquefy hydrogen, all of the refrigeration could be supplied at 20K. However, far more than half the heat removal is required to cool the gas (which is finally liquefied) from room temperature to 80K, where heat can be removed at one fourth the power requirement. Even the problem of removing a small amount of heat at a low temperature, say 15K, results in refrigeration loads at other temperatures. There is always thermal conductivity through cylinders and regenerators, and radiation heat leak into the system. This heat can be much more conveniently pumped out at 80 - 100K by the use of a cooled radiation shield. Adding the radiation heat leak to the 15K load greatly increases compressor power requirements.

The second reason for it being desirable to have refrigeration available at different temperature levels is the capability for reducing the design requirements of the components, such as heat exchangers and regenerators.

In any low-temperature refrigeration system, a heat exchanger or regenerator is used to prevent losses of refrigeration. The refrigeration loss, Q_r, is

$$Q_r = \dot{M} C_p \Delta T_e , \tag{4}$$

where

$\dot{M}$ = the mass flow of gas,

C_p = heat capacity,

and

ΔT_e = the temperature difference between the gas entering and leaving the heat exchanger.

The gas flow $\dot{M}$ produces in its expansion a refrigerating ΔT_r. Thus, ΔT_e must be smaller than ΔT_r, or all the refrigeration produced would be lost. And ΔT_r is also proportional to the temperature at which expansion occurs. Typically, with these devices, ΔT_r is equal to 0.3T, where T is the temperature in degrees K. If the expansion space were to be operated at 10K, ΔT_r would be 3K. If there is to be some useful refrigeration and if other refrigeration losses are to be handled, ΔT_e has to be 1K or better. To achieve such a ΔT across the temperature interval 10 - 300K requires a heat exchanger or regenerator of about 99.7% efficiency. This is essentially impossible, for balanced-flow heat exchangers cannot be made this efficient. Even regenerators probably could not be conveniently made this efficient.

If, however, we use a three-stage system and have another stage at 40K, a ΔT_e of 1K can easily be achieved across the 10 - 40K temperature span. A heat exchanger of 97% efficiency would give some useful refrigeration as above, and it can be built. Of course with a three-stage system, three regenerators are required. However, all three together require much less area than would be required for similar performance from a one- or two-stage system. Adding stages reduces the total amount of regenerator area and volume required for equivalent performance.

The heart of these refrigerators is the regenerators. For them to function, it is necessary that they be filled with a matrix material having substantial heat capacity. Since the heat capacity of solids falls to very near zero at low temperatures, a limit is set on the temperatures which can be achieved. With materials like brass, bronze and steel, the limit is about 35K; with lead, it is about 13K or 14K. Lead seems to be the best possible solid material.

A Heat-Pump Helium-Liquefier System

A three-stage refrigerator can generate refrigeration efficiently at a temperature as low as 14K. This is, of course, well below the Joule-Thomson (J-T) inversion points for helium. Thus, a helium-temperature refrigerator or liquefier can be made by the addition of a system of heat exchangers, which precools the high-pressure helium to 14K before it is passed through a J-T heat exchanger and valve. This considerably increases the complexity of the system.

Figure 4 shows schematically a complete helium-liquefier system added to a three-stage low-temperature heat pump. Seven additional heat exchangers are required for this system. Four of them are counterflow heat exchangers that cool the J-T high-pressure gas stream with the exhausting low-pressure gas stream. The other three are constant-temperature heat exchangers which supply from the refrigerator the refrigeration required to cool the gas that eventually liquefies; they also overcome the inefficiencies of the four J-T-stream counterflow heat exchangers.

Better refrigerator-power efficiency is achieved with compression ratios of three or four to one between about 80 psia and 280 psia. To liquefy helium, however, we must expand the J-T gas stream to 1 atm. The liquefier therefore has three operating pressures: 15 psia 80 psia and 280 psia. About 90% of the gas operates in the range of 80 - 280 psia and runs the refrigerator. The remaining 10% flows through the J-T system for liquefaction and drops through the J-T valve from 280 psia to 15 psia.

Description of An Actual Refrigeration System

The discussion earlier in this paper has shown how the simple refrigeration cycle described can be expanded into a three-stage unit providing refrigeration at three different temperature levels. It has also been shown how this refrigeration can be utilized to cool a secondary circuit of gas to the extent that J-T expansion can be utilized to achieve refrigeration at even lower temperatures. To add to this theoretical discussion, we are privileged to describe one of several actual refrigeration systems developed from this concept. This particular system was chosen not only because it is representative of the new cycle's possible applications but because it has reached a degree of performance and development that make it unique in the field of low-temperature refrigeration.

The subject refrigeration system has been designed to cool and maintain a small electronic device at 4.2K; it is capable of continuous operation under a wide range of ambient conditions. The system is comprised of a refrigerator unit and a compressor unit with the associated interconnecting piping. The system is self-contained in that only electrical power and cooling air for the compressor are required. Figures 5 and 6 are photographs of the refrigerator and compressor units, respectively.

The refrigerator unit, containing the electronic device and its supporting structure, is capable of operation in any orientation; the compressor unit, somewhat larger and heavier, is mounted some distance from the refrigerator unit and operates only in a single-plane orientation. The compressor unit supplies gas, in this case helium, to the refrigerator unit at the proper pressure (280 psia) and at the proper flow rate; return gas from the refrigerator unit is delivered back to the compressor unit at two different pressures: nominally 80 psia and 15 psia. The interconnecting piping transfers the gas between the compressor and refrigerator units while, for this specific application, accommodating the relative motion between the two. More detailed descriptions of the refrigerator and compressor units follow.

Refrigerator Unit

The refrigerator unit consists, in the main, of a refrigerator circuit, a mechanical drive unit, a J-T circuit, a radiation shield, and a vacuum insulation jacket with associated vacuum pumps. The refrigerator circuit contains, as previously described, a displacer and cylinder, a regenerator, and half of a constant-temperature heat exchanger (heat station) for each of the three stages. The three cylinders and displacers extend from the ambient-temperature supporting flange to their respective temperature levels, the lower temperature levels being more remote from the ambient-temperature flange because of heat-leak considerations. The three regenerators bridge each of the adjacent temperature levels the three heat stations are located directly at the three temperature levels Figure 7 shows this arrangement quite clearly and indicates the relative size of the various components. The operating temperatures of the three temperature levels are nominally 80K, 35K, and 14K, with the helium supply pressure set at approximately 280 psia and the return at about 80 psia.

A mechanical drive unit, commonly referred to as the crosshead, moves the three displacers up and down in unison and also operates supply and exhaust valves synchronously in proper phase relationship to the displacers. The three displacers move in the required, prescribed pattern through a stroke of approximately 1 in. at a frequency of about 105 cycles per minute. The crosshead and displacers are the refrigerator's only moving parts. (See Figure 8.)

The J-T circuit consists of a series of counterflow heat exchangers connected between each of the adjacent temperature levels; a final exchanger is located between the last stage of refrigeration (14K) and a liquid-helium stage. The other halves of the constant-temperature heat exchangers that make up the three heat stations are connected in series with the incoming high-pressure side of the counterflow heat exchangers. This allows the refrigerator to extract the heat from the J-T gas stream at the three temperature levels of available refrigeration. The liquid-helium stage consists of a valve for the J-T expansion, a charcoal trap immediately upstream of this valve, a liquid reservoir downstream of the valve, and a flange for thermal bonding of the liquid-helium stage to the electronic device. The J-T expansion valve is of the needle type; it is adjustable by means of a long stem and a micrometer head external to the ambient temperature flange. Because the orifice in the valve is extremely small, a charcoal trap is used to keep the stream of helium gas entering the J-T valve absolutely clean. A second charcoal trap is inserted in the incoming J-T gas stream just ahead of the 35K heat station for primary-gas clean-up. The liquid reservoir is a hollow copper sphere with a centrally located outlet that provides a relatively constant volume of liquid helium irrespective of the refrigerator's orientation. This spherical reservoir also contains the bulb of a helium vapor-pressure thermometer system for external monitoring of the liquid-helium temperature. Figure 9 shows the J-T circuit components and crosshead assembled on the basic refrigerator.

A radiation shield is thermally bonded to the 80K heat station so that the major portion of the radiant energy from the ambient-temperature surroundings may be removed by the refrigeration available at this temperature level. The much smaller amount of radiant energy transmitted between this 80K shield and the lower-temperature components does not warrant the complexity of additional shielding. The shield is covered by a multilayer mat of alternate aluminum foil and an insulating fabric to further reduce the amount of radiant energy absorbed by the 80K heat station.

The vacuum jacket, essentially the external shell of the refrigerator, surrounds all of the components described above; within this jacket a vacuum of the order of 10^{-4} - 10^{-5} mm Hg or lower is maintained. The pumping of this vacuum can be accomplished by a conventional diffusion pump; but because of operational requirements, this particular refrigerator unit has been fitted with a new ion pump capable of maintaining the required vacuum in any orientation without a forepump. Figure 5 shows these pumps connected to the vacuum jacket, it also shows the crosshead mounted in place.

Compressor Unit

The compressor unit consists mainly of a modified commercially available hermetic compressor and a helium purification system. The compressor unit is modified so as to permit the two pistons and cylinders to operate independently; this arrangement provides for compression in two stages. The high-pressure supply to the refrigerator and J-T circuits is the discharge of the second, or high-pressure, stage of this compressor; the J-T return is the inlet to the first, or low-pressure, stage; and the refrigerator return, along with the first-stage discharge, constitutes the second-stage, or intermediate, inlet. Further modifications to the compressor provide for oil injection directly into the cylinders for cooling, lubrication, and sealing purposes. An oil pump and oil-to-air heat exchanger are also included. Means of removing particulate and vaporized oil from the discharge helium stream are incorporated to insure that no impurities are frozen out within the cold regions of the refrigerator or J-T circuits. Although the refrigerator circuit has something of a self-cleaning section, minute quantities of impurities that enter the J-T circuit can seriously affect over-all performance. Figure 6 shows the compressor unit in the form dictated by this particular application.

Performance and Descriptive Data

Considerable operating time has been accumulated to date on the refrigerator system described above. The system has been thoroughly tested; it has been put into operational service and has had over 400 hr of running time. A second system is being assembled and will be used as a basis for further development and testing.

The refrigeration system reduces approximately 750 milliwatts of useful refrigeration at 4.2K with corresponding smaller amounts of refrigeration at those lower temperatures which are within the capability of the compressor unit.

Temperature stability has been demonstrated to be within $\pm$ 0.06C, independent of the refrigerator orientation, normal ambient temperature and pressure conditions, and nominal-refrigeration load variations. If liquid nitrogen is used for precooling, the system can be brought from ambient to 4.2K in about five hours, although this time interval is very dependent on the thermal mass of the object to be refrigerated.

The refrigerator unit is about 15 in. by 12 in. by 28 in. (exclusive of the projection of the vacuum jacket to accommodate the electronic device); it weighs about 90 lb (exclusive of the permanent magnets required for the vacuum pumps) and requires less than 100w of electrical power. Ample space is provided for the device to be refrigerated, as can be seen in Figure 9.

The compressor unit is about 22 in. by 24 in. by 75 in.; it weighs about 700 lb and requires 3 kw of electrical power and free access to air for cooling.

Conclusion

The refrigeration system described is one example of the applications potential of the new multistage refrigeration principle. We believe that the application presented here demonstrates the simplicity, versatility, and reliability predicted of this new refrigeration cycle when it was first introduced. Future development will result in longer service life, more compact and lighter-weight units, increased efficiency, and, we sincerely hope, more widespread usage in varied applications.

References

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2. W. E. Gifford and H. O. McMahon, "A New Low-Temperature Gas-Expansion Cycle" (Parts I and II), Proceedings of the 1959 Cryogenics Engineering Conference, vol. V, September, 1959 pp. 354-372.

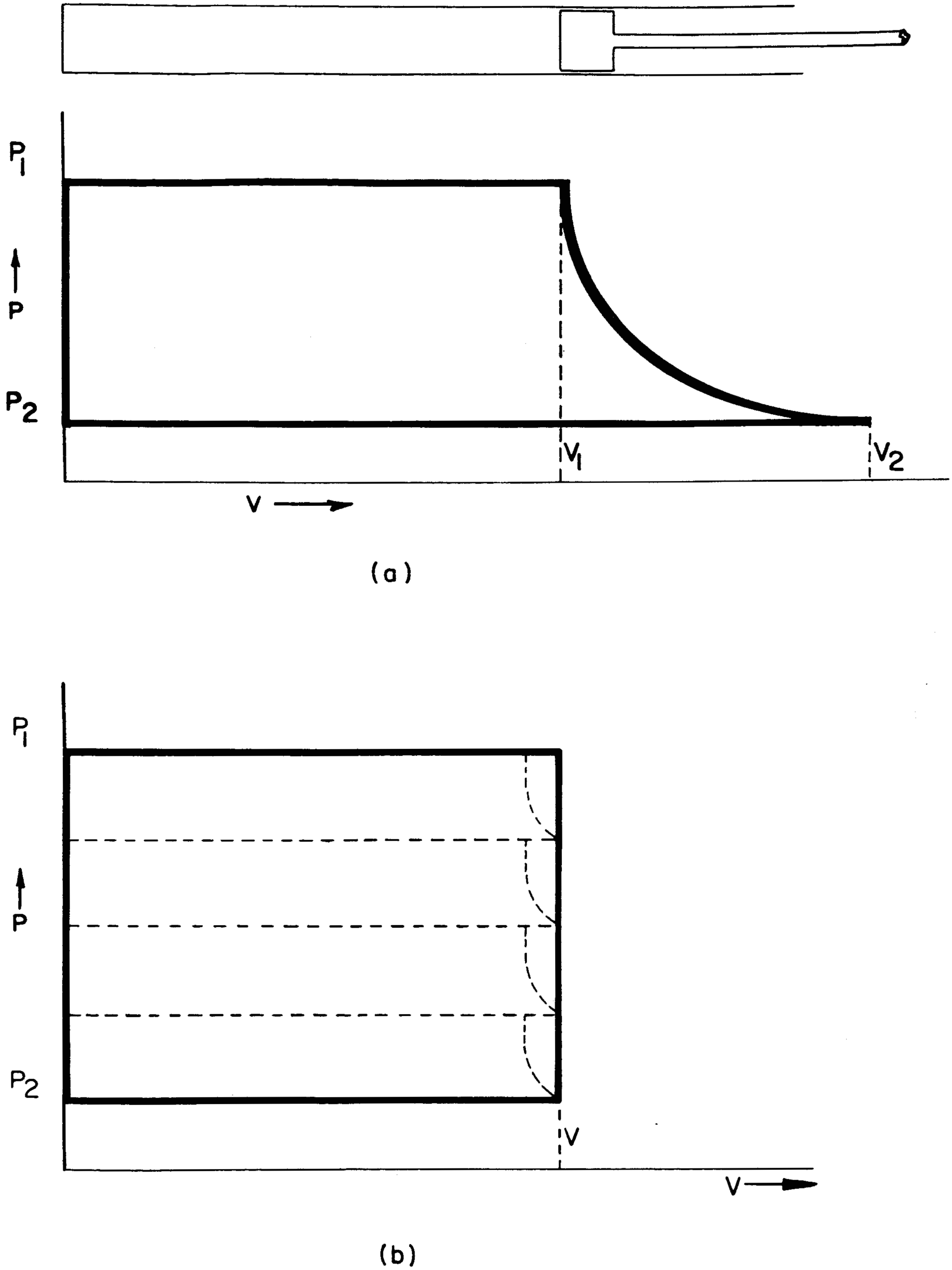

FIG. 1

EXPANSION ENGINE DIAGRAMS

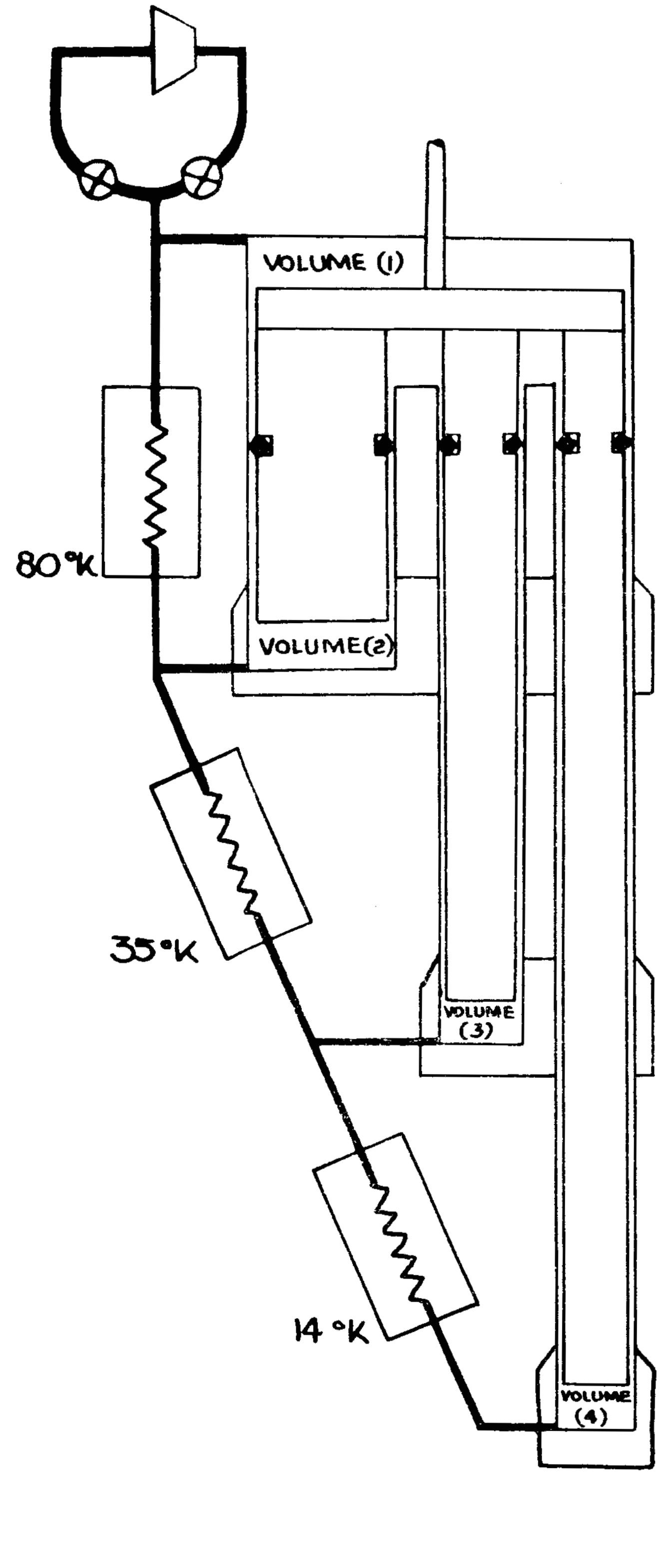

FIG. 2

SCHEMATIC OF MULTI-STAGE HEAT PUMP

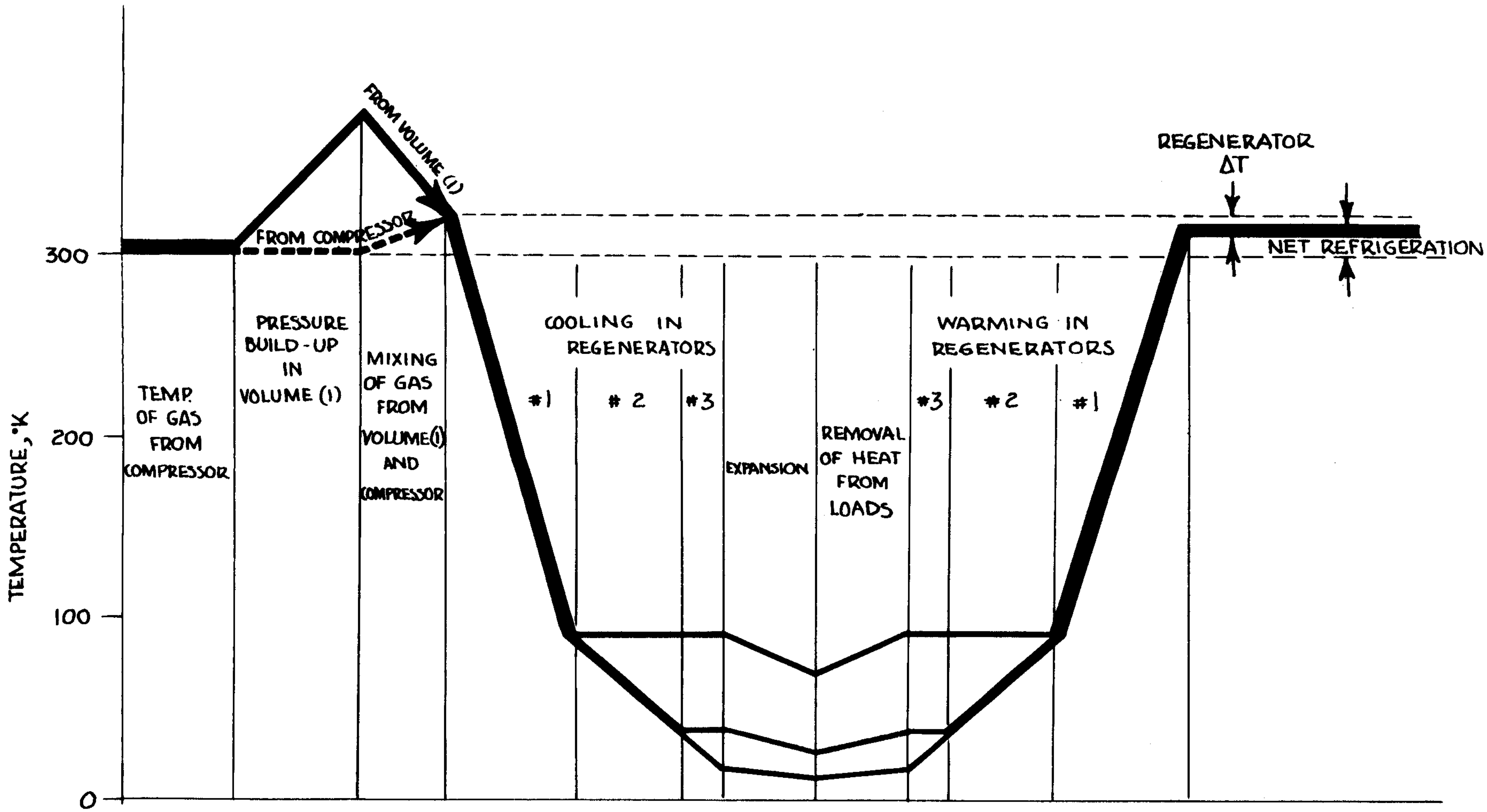

FIG. 3

TEMPERATURE HISTORY OF LOW TEMPERATURE MULTI-STAGE HEAT PUMP CYCLE

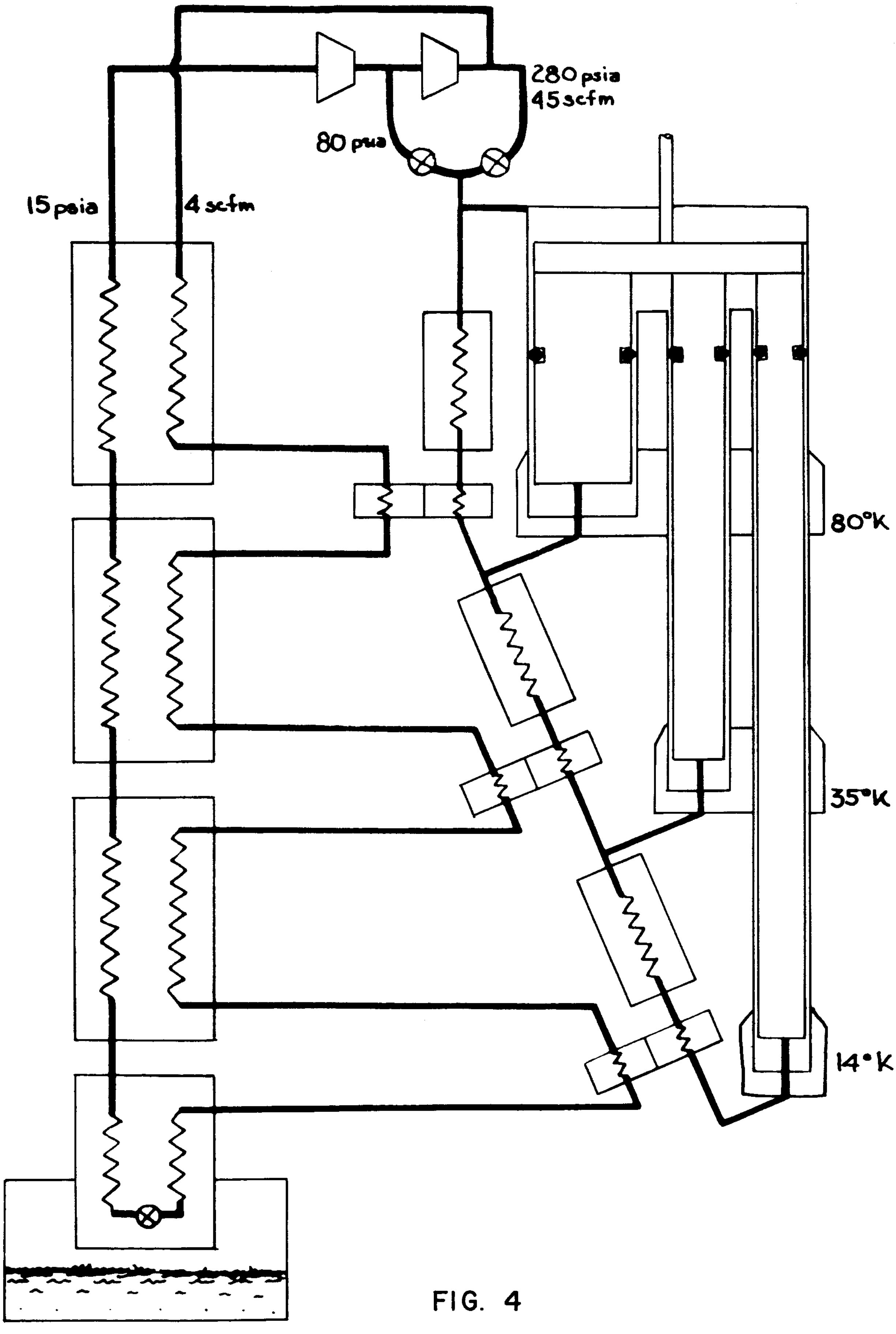

FIG. 4

SCHEMATIC OF HEAT PUMP HELIUM LIQUEFIER

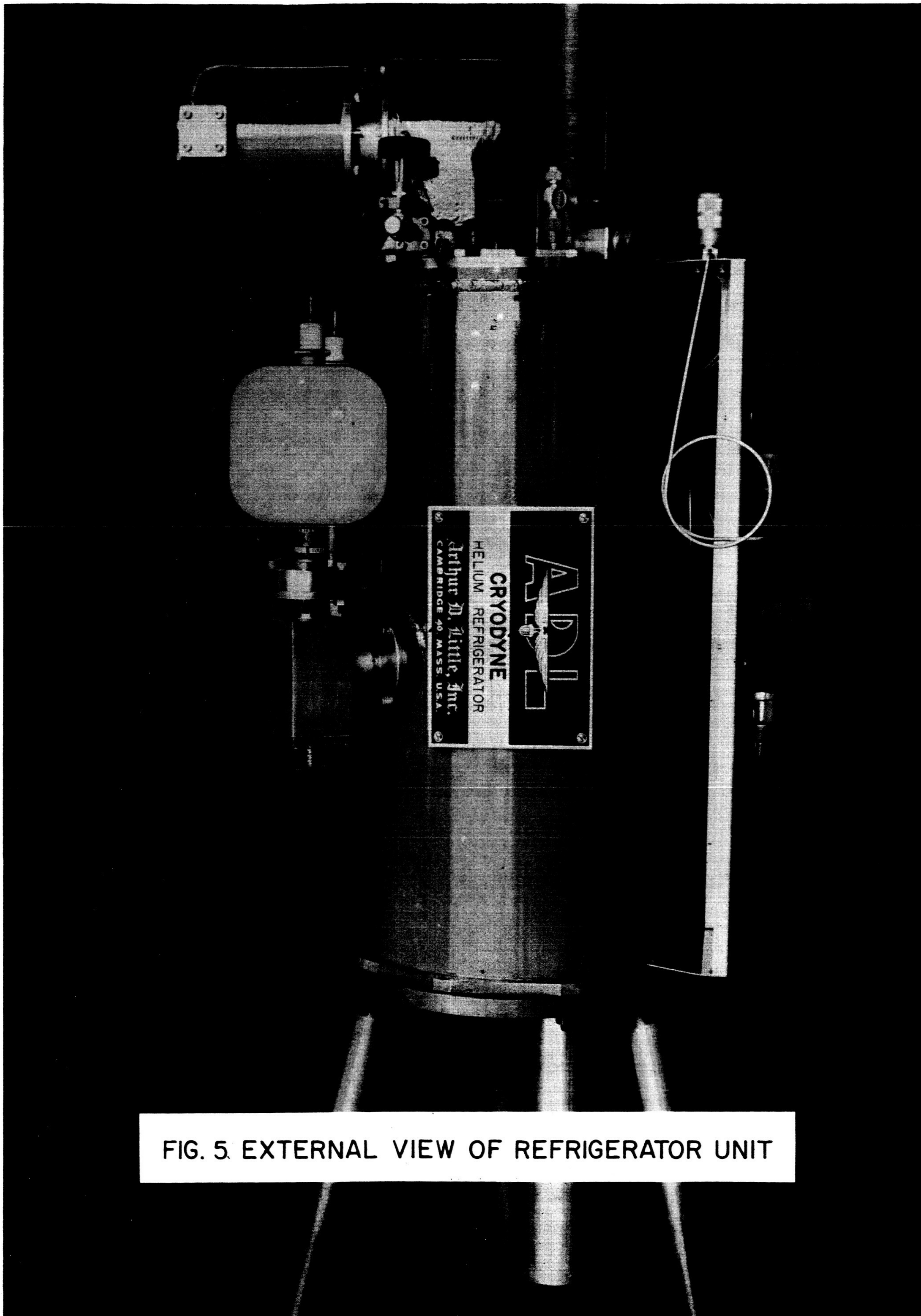

FIG. 5. EXTERNAL VIEW OF REFRIGERATOR UNIT

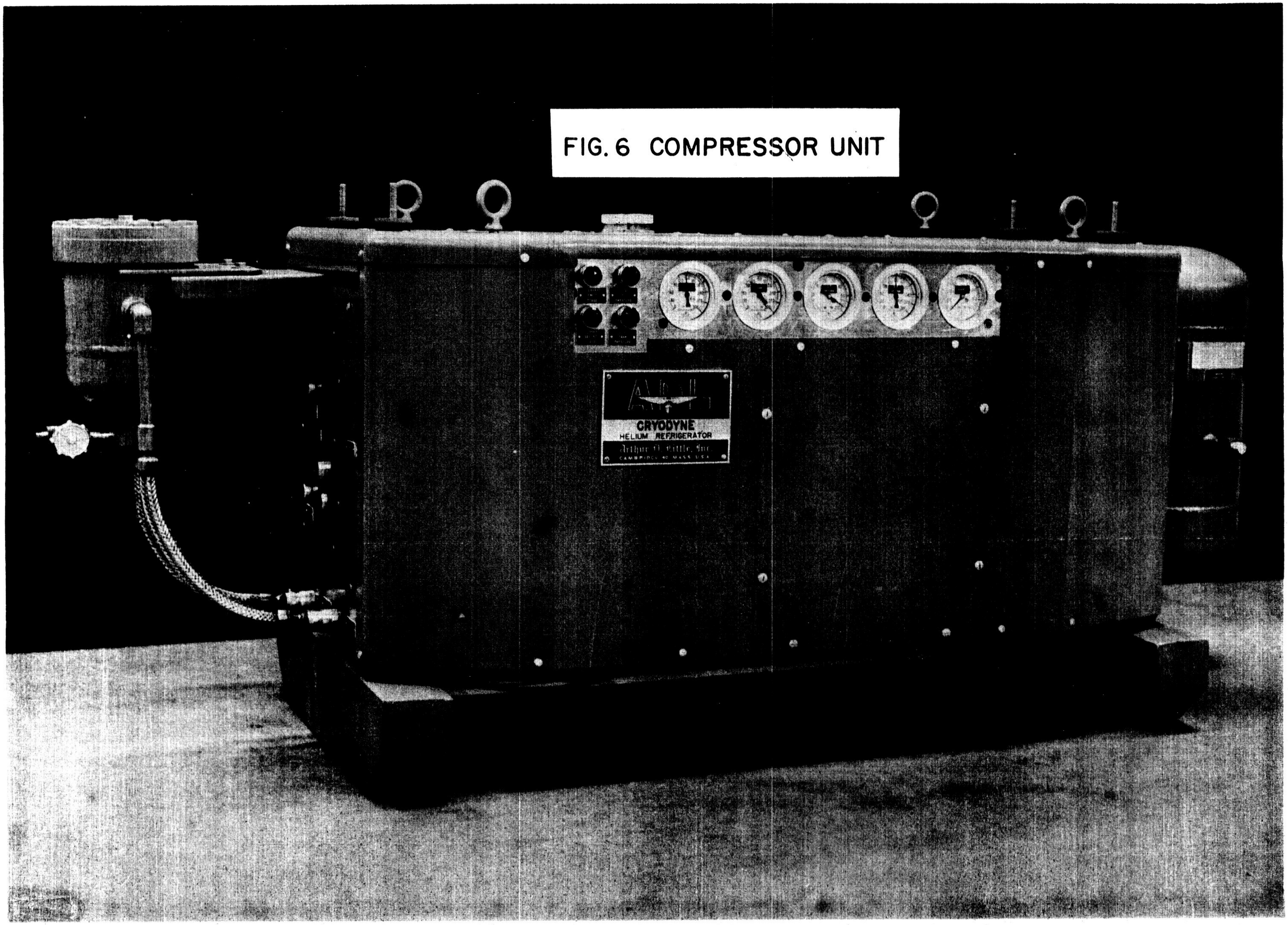

FIG. 6 COMPRESSOR UNIT

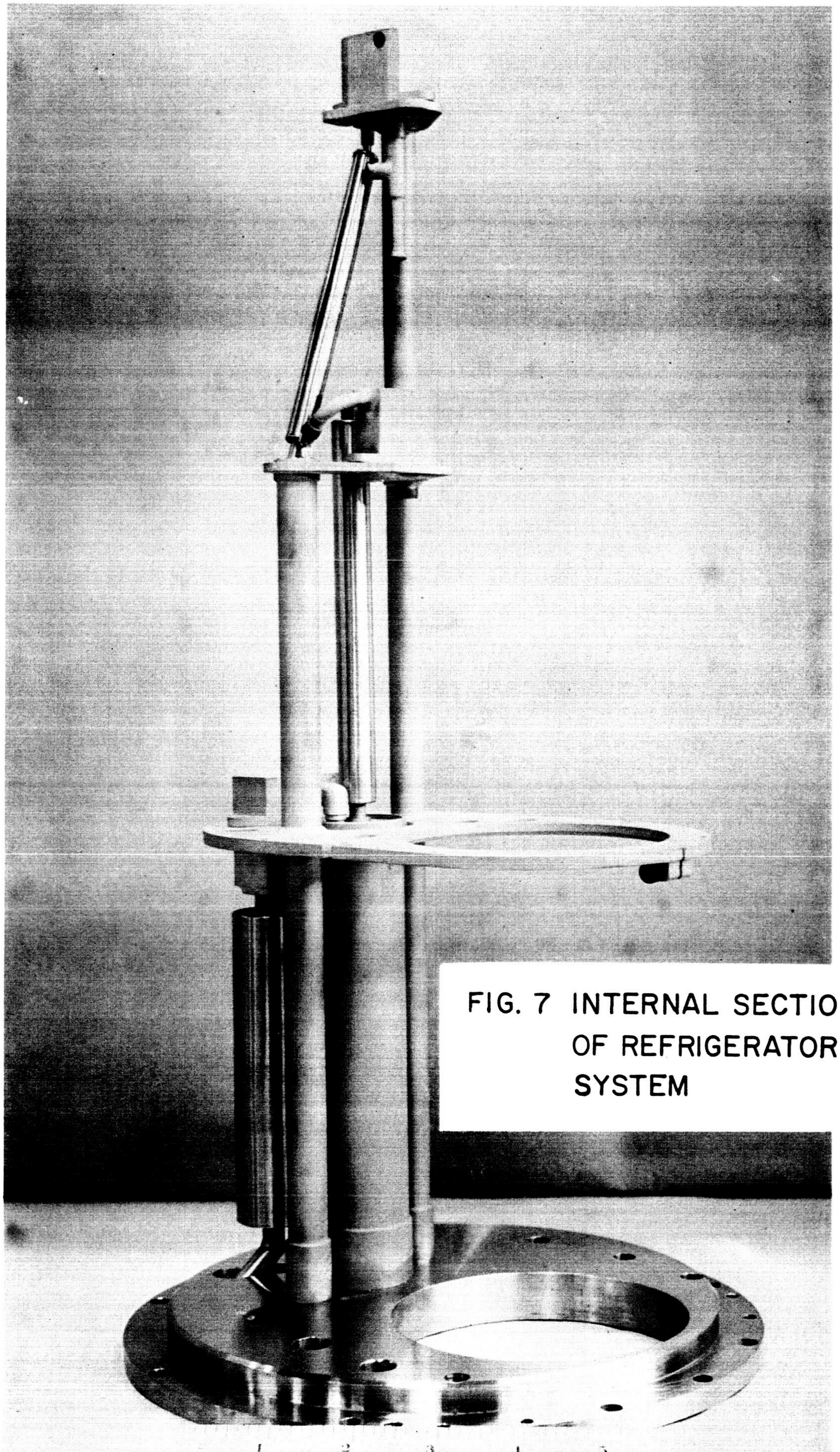

FIG. 7 INTERNAL SECTION OF REFRIGERATOR SYSTEM

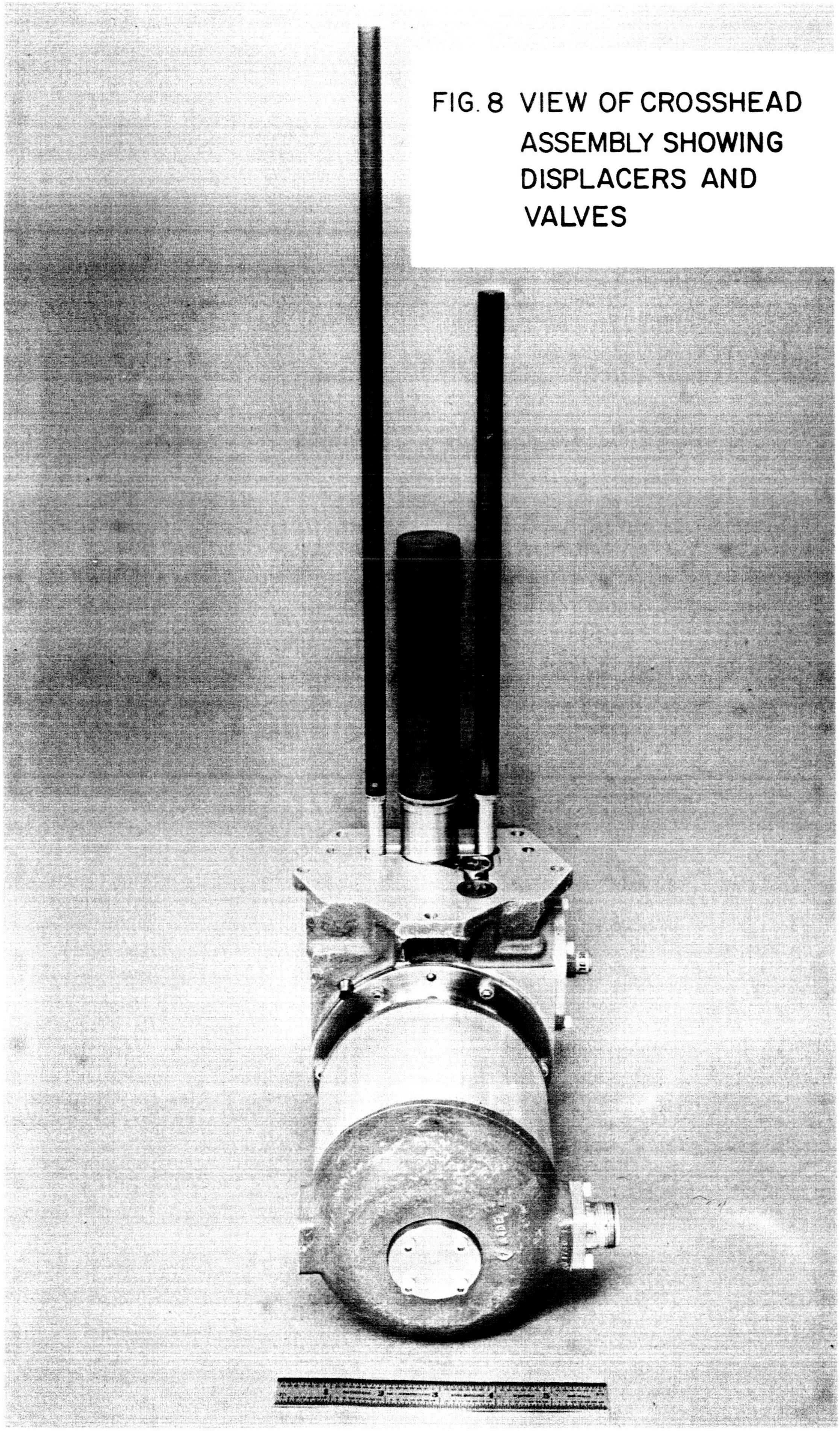

FIG. 8 VIEW OF CROSSHEAD ASSEMBLY SHOWING DISPLACERS AND VALVES

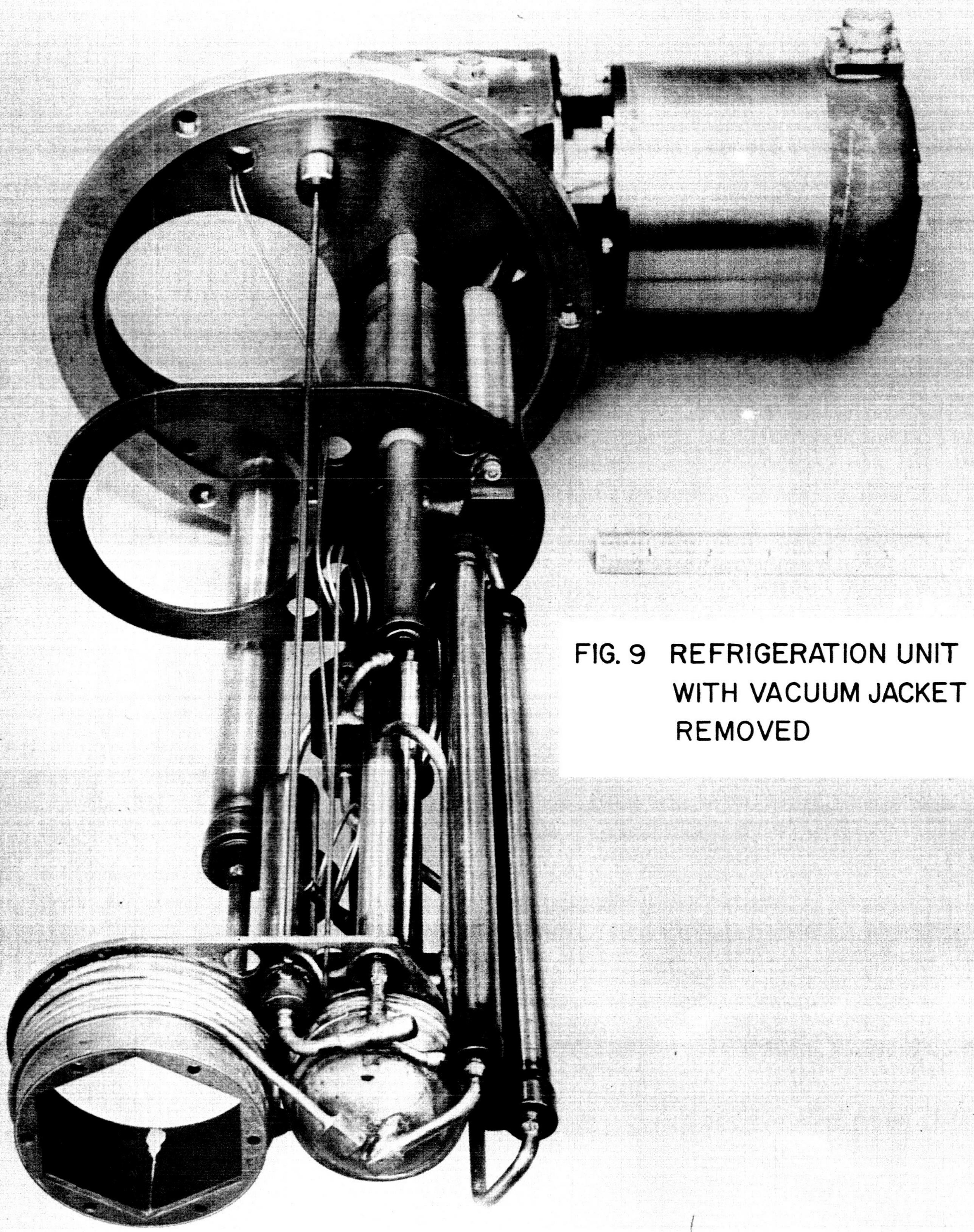

FIG. 9 REFRIGERATION UNIT WITH VACUUM JACKET REMOVED